

Adult Discrimination Performance for Pediatric Acuity Test Optotypes

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PURPOSE. To compare adult discrimination performance on nine pediatric visual acuity tests to determine the consistency of optotype design.

METHODS. After their binocular acuity was measured with each test, eight adult observers (mean age, 27 years \pm 6.3 SD; three emmetropes and five corrected myopes) were shown isolated single optotypes from the Allen figures, HOTV, Landolt C, Lea Numbers, Lea Symbols, Lighthouse, Patti Pics, Precision Vision numbers, and Tumbling E tests. A one-interval, two-alternative forced-choice protocol was used at a single distance, and each optotype was paired with all optotypes from the same chart. Confusion matrices were generated for each test and Luce's (1963) biased-choice model was fit to each matrix to derive measures of pairwise similarity between the optotypes.

RESULTS. The acuities from the Allen figures ($P < 0.001$) and HOTV ($P = 0.029$) were the only ones to differ significantly from the reference Landolt C. The choice-model analyses of the confusion matrices revealed that the Allen figures, HOTV, Lighthouse, Patti Pics, and Precision Vision numbers tests all had significant differences in discriminability of optotypes within the test.

CONCLUSIONS. Pediatric acuity test optotypes are not all equally discriminable to adult observers with normal vision and no ocular disorders. The current data suggest that care must be taken when presenting limited numbers of optotypes, as is done with young patients. (*Invest Ophthalmol Vis Sci.* 2011; 52:4307–4313) DOI:10.1167/iops.10-6391

In 1980, the Committee on Vision set guidelines for the construction of visual acuity charts.¹ An important consideration was that optotypes at the same acuity level be equally discriminable. This issue was minor for one of their two recommended optotypes, the Landolt C, because all Landolt C optotypes are identical except for the variable location of the gap in the circle. The other test was based on the use of letter optotypes, for which the discriminability of individual optotypes varies.^{2–5}

Based on the recommendations of the committee, Ferris et al.⁶ created the Early Treatment of Diabetic Retinopathy Study (ETDRS) acuity charts. The optotypes are 10 letters, found by

Sloan et al.⁴ to be somewhat different in difficulty of discrimination. They are organized so that the optotypes on each line combine to an approximately equal average difficulty per line. Several investigators have studied the discriminability of these letters and have found, in particular, that the curved letters are typically more difficult to identify than the angular ones.^{4,7,8}

Numerous visual acuity tests have been constructed for the assessment of children who cannot perform the Landolt C test or identify letters for ETDRS and other letter acuity charts. Many of them require recognition of optotypes in the presence of crowding or contour interaction, which is advantageous in the detection of amblyopia.^{9–16} Several organizations have therefore developed guidelines for acuity assessment of young patients with a range of recognition acuity tests, including Snellen Letters, Snellen Numbers, Tumbling E, HOTV, and picture tests, such as the Allen figures and Lea symbols.^{17,18}

The variability of the acuity results across pediatric tests has been documented in within-subject comparisons for some tests,^{10,19–25} and these studies have typically found differences in acuity between tests that should be taken into account in the interpretation of clinical results. Although the developer of one pediatric test has compared the discriminability of the optotypes in the test to the discriminability of Landolt C optotypes (Hyvarinen L, personal communication with VD, 1999), the discriminability of optotypes in other pediatric visual acuity tests has not been studied.

The purpose of the present study was to compare adult subjects' discrimination of the optotypes in commercially available pediatric acuity tests, to provide guidelines for interpreting differences between test results on the basis of the basic optotype design, and to provide guidance for further test development. Although these tests are designed for use with pediatric patients, adult subjects were tested first to reduce noise in the data from varying levels of attention and cooperation and to enable a full within-subject comparison of all pairs of optotypes to be performed for each subject (74 pairs). It was anticipated that typically developing young children would not be capable of completing a full set of comparisons, but that the effect of optotype spatial frequency content and design would be similar to that for adults. This approach can be extended to data collection from children or patients with vision loss.

METHODS

Subjects

The subjects were four male and four female adults, 21 to 41 years of age (mean 27 years \pm 6.3 SD), who had no ocular disorders and wore their habitual optical corrections if needed (three subjects were uncorrected emmetropes and five were myopes of less than 8.00 D corrected with spectacles or soft contact lenses). All the subjects had ETDRS letter chart acuities of -0.08 or better. None of the subjects had significant previous experience with visual psychophysics. The research adhered to the tenets of the Declaration of Helsinki and informed consent was obtained from each subject after the protocol

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Pediatric Acuity Charts

Eight commercially available pediatric acuity charts were used. The Allen figures (Hilco, Plainville, MA) were uncrowded single figures and the HOTV (Precision Vision, La Salle, IL, Cat. No. 2014), Lea Numbers (Good-Lite, Elgin, IL, #250100), Lea Symbols (Good-Lite, Elgin, IL, #271100), Lighthouse figures (Precision Vision, La Salle, IL, Cat. No. 3401), Patti Pics (Precision Vision, La Salle, IL, Cat. No. 2501), PV numbers (Precision Vision, La Salle, IL, Cat. No. 2711) and the Tumbling E (Precision Vision, La Salle, IL, Cat. No. 2316) charts were all standard, uncrowded, logarithmic line charts. The Landolt C test (Precision Vision, La Salle, IL, Cat. No. 2205) was included, as a ninth test, to provide data from an acuity test that was recommended as a standard by the Committee on Vision.¹

Optotype Stimuli

Each different optotype from each test was scanned, scaled in size to the 20/40 optotype for that test, and printed singly at the same high contrast. The border of each print was then cut to the same size for each test and mounted on a 12.7 × 15.2-cm piece of white cardboard, to ensure that the isolated optotypes could not be discriminated using any aspect of their background or mounting. The optotypes were also checked carefully for printing blemishes.

Phase 1: Assessment of Visual Acuity

First, acuities for each test in full chart format were measured to determine the threshold viewing distance for testing discriminability of the 20/40 optotypes. Each subject's visual acuity (VA) was measured binocularly with 11 commercial VA charts, including the nine described above plus the Bailey-Lovie (Multimedia Center, University of California, Berkeley) and ETDRS (Precision Vision, La Salle, IL) tests, which are commonly used to test adult acuity. The order of test presentation was randomized across observers and, as designed by the manufacturers, the testing distance was 3 m for all tests except the Allen figures (see below). VA was scored in logMAR format. For all charts except the Allen figures, 0.02 log unit (equal to 1 optotype on a 5-optotype-per-line chart) was subtracted for each optotype read correctly on the line after the last fully correct line. In this chart format, these tests all have five optotypes per line, so reading all optotypes correctly on a line changed the acuity result by a full 0.1-log-unit step. Acuity for the Allen figures was determined using the protocol provided with the test. The viewing distance was increased to the greatest distance at which three of the figures were consistently recognized.

Phase 2: Assessment of Similarity

The acuity data were then used to derive a viewing distance for the second phase of the project, which used the isolated 20/40 optotype stimuli. Each subject was positioned at a distance calculated to compensate for their individual acuity level. This was done by taking their average acuity across the tests and calculating the equivalent threshold distance for a 20/40 optotype. For example, a subject with an average acuity of logMAR 0 (20/20) would be placed at 40 feet for the 20/40 task. The eight subjects were tested in the second phase at the following eight distances: 35, 55, 47, 47, 52, 44, 45, and 42 feet (average acuities from 20/23 to 20/14). These distances were confirmed to be appropriate by collecting pilot data.

Subjects were presented with blocks of 10 trials in which two optotypes from an acuity test were each presented five times. They were told which pair they were working with before starting the block. On each trial the subject's task was to state which of the two optotypes had been presented. Each trial was therefore a one-interval, two-alternative forced-choice (2 AFC) presentation. The order of the 10 trials within each block was predetermined and pseudorandom, with no more than three consecutive trials of the same optotype.

Viewing was binocular, and each presentation lasted until the subject responded. Across blocks, each optotype was paired with all the other optotypes from the same chart, and across the nine pediatric acuity tests, 74 different optotype pairings were tested: 21 from the Allen figures; 6 each from the HOTV, Lea Numbers, Lea Symbols, Tumbling E and Landolt C charts; 3 from the Lighthouse; and 10 each from Patti Pics and PV numbers. The order of presentation of the 74 pairs was prandomized and when every pair had been presented a second set of 10-trial blocks of each pair was shown, with the order of trials in each block reversed. Data collection took approximately 10 hours for

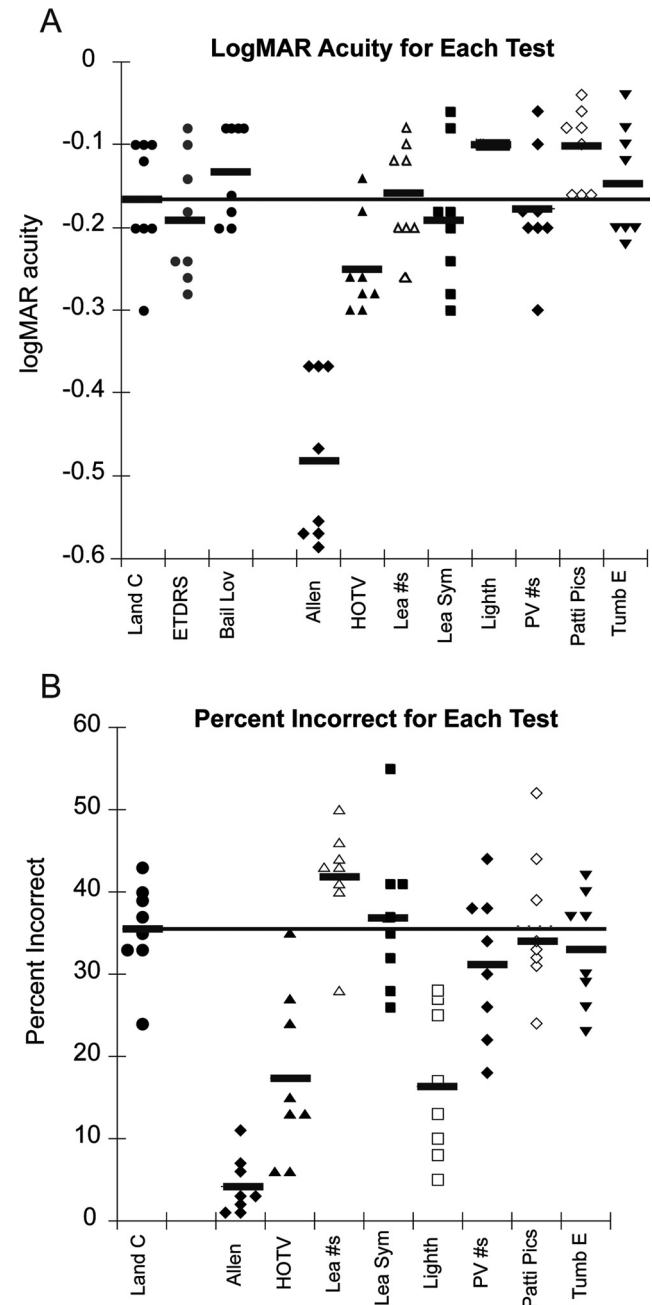


FIGURE 1. (A) LogMAR acuity values for each acuity test. Individual subjects' acuities are represented by the symbols, and the mean for each test by the horizontal lines. The extended horizontal line provides a comparison with the Landolt C data. (B) Percent incorrect for the paired optotype psychophysics. The data have been combined, to form an average value for each subject for each test. The horizontal lines represent the mean for each test and can be compared with the extended line representing the Landolt C mean value.

each subject, split into sessions of 2 hours each with regular breaks to avoid fatigue. The sessions all took place within a 2-week period for each subject.

RESULTS

Phase 1: Assessment of VA

The VA data are shown in Figure 1A. The mean LogMAR acuity across subjects and the individual subject values are plotted for each test. The Landolt C, ETDRS, and Bailey-Lovie results are shown on the left side of the figure, for comparison with the data from the pediatric tests shown on the right. A repeated-measures ANOVA indicated that acuity varied significantly across tests ($F_{(10,70)} = 29.32$; $P < 0.0001$). Using the Landolt C as a standard reference test,¹ post hoc comparisons with Bonferroni correction between the Landolt C test and each of the other tests indicated that the Landolt C acuities were significantly different from those obtained using the Allen figures ($P < 0.001$) and the HOTV ($P = 0.029$) tests, but were not significantly different from the remaining tests (all $P > 0.20$). It should be noted that the Lighthouse test demonstrated a floor effect, in that all the subjects reached the lowest line of the test, labeled 20/16.

Phase 2: Assessment of Similarity

The percentage of incorrect responses for the isolated optotype, fixed-distance task is shown for each of the tests and subjects in Figure 1B. The percent incorrect is plotted, rather than the percent correct, to maintain a consistent relationship with Figure 1A—lower values represent easier tests. A repeated-measures ANOVA indicated that the percent incorrect varied significantly across tests ($F_{(8,56)} = 35.30$, $P < 0.0001$). With the Landolt C as a standard reference test,¹ post hoc comparisons with Bonferroni correction between that test and each of the other tests indicated that the Landolt C values were significantly different from those obtained with the Allen figures ($P < 0.001$) and the HOTV ($P = 0.001$) and Lighthouse tests ($P < 0.001$) and were not significantly different from the remaining tests (all $P > 0.25$).

The proportion of correct responses for each optotype, averaged across all the forced-choice tests and subjects, is presented in Figure 2. Each optotype is also labeled according to the test it came from. The optotypes are shown in ascending order of correct responses, with the easiest to identify therefore having the highest values. The figure demonstrates that

the performance for individual optotypes spanned the full range, from close to the guessing rate of 50% in this 2-AFC task, up to close to 100% correct. The change in performance across optotypes is gradual on the left side of the figure, indicating that a relatively large group of symbols resulted in similar performance, while the right side of the figure shows a steeper change (from ~65% to 100% correct). Several of the optotypes from the Allen figures are grouped at the ceiling performance of close to 100% correct. This figure highlights the range of performance for optotypes designed to test the same acuity level.

The paired optotype data were then combined across subjects to form a single confusion matrix for each test, as shown in Table 1. Each row in each matrix represents the stimulus (i) that was presented during a trial, and each column represents the response (j) that was made. Each off-diagonal cell entry (i, j) gives the frequency with which response j was made on trials in which stimulus i was presented and pair (i, j) was the known pair being tested in that block. For example, in the HOTV test, on trials in which H was presented, and (H, O) was the known pair, subjects incorrectly identified the letter as an O on 11 trials. The diagonal cell entries in each confusion matrix give the total number of correct responses across all the forced-choice tests involving the row stimulus.

A maximum likelihood approach was used to fit Luce's (1963) biased-choice model to these data.² This is a standard model for examining identification data and uses the confusion matrix to estimate one set of parameters representing the bias of observers toward making each response and another set of parameters representing the similarity of each pair of stimuli, in this case optotypes. The model is as follows:

$$P[j | (i, j)] = \frac{b_j s}{b_i + b_j s_{ij}}$$

where $P[j | (i, j)]$ is the probability that response j was given when stimulus i was presented and the known pair being tested was i and j ; b_i is the bias to responding i , b_j is the bias to responding j , and s_{ij} is the similarity of i to j . The similarities are scaled so that the similarity of an optotype to itself is given a value of 1. The bias values are constrained to fall between 0 and 1 and to sum to 1. In the case of nondifferential bias, each estimated bias parameter for the optotypes in a given test would be equal to $1/N$, where N is the number of optotypes in the test.

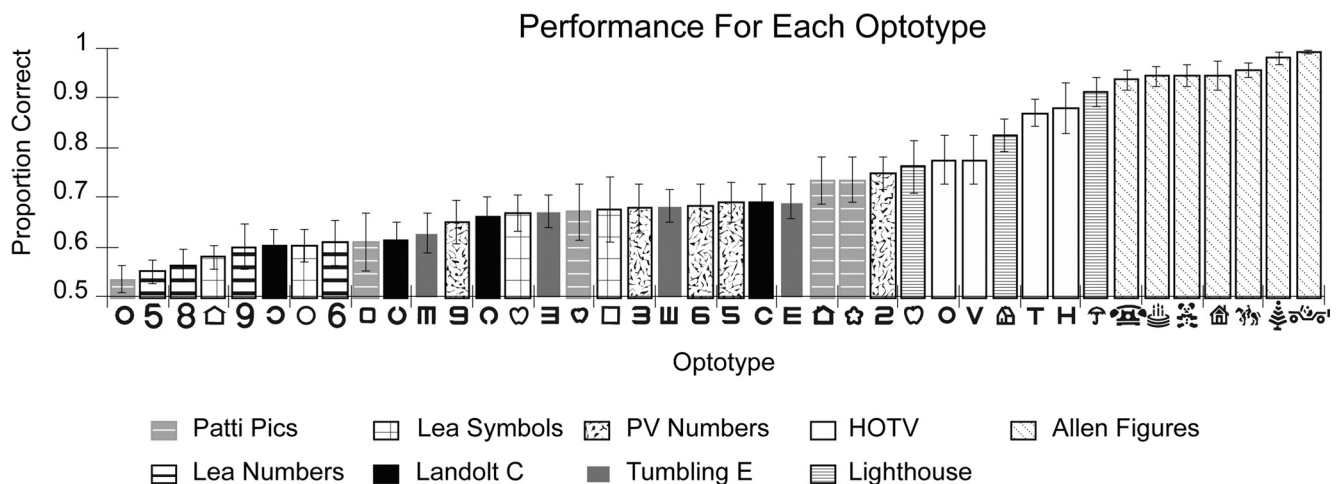


FIGURE 2. Proportion of correct responses for the paired optotype psychophysics task. The data have been combined across subjects and optotype pairs to generate a mean (\pm SD across subjects) for each optotype from the different tests.

TABLE 1. Confusion Matrices

HOTV				
	Response			
	H	O	T	V
Stimulus				
H	211	11	5	13
O	22	186	13	19
T	0	5	209	26
V	10	8	36	186
Landolt C				
	Response			
	Up	Down	Left	Right
Stimulus				
U	147	33	31	29
D	27	159	30	24
L	40	29	145	26
R	25	29	20	166
Tumbling E				
	Response			
	Up	Down	Left	Right
Stimulus				
U	164	26	24	26
D	30	151	34	25
L	22	31	161	26
R	32	20	22	166
Lea Numbers				
	Response			
	5	6	8	9
Stimulus				
5	132	31	40	37
6	32	146	28	34
8	42	33	135	30
9	37	29	30	144
Lea Symbols				
	Response			
	House	Apple	Square	Circle
Stimulus				
House	139	30	40	31
Apple	23	160	30	27
Square	27	28	162	23
Circle	32	32	31	145

(continues)

The similarity values for each pair of optotypes within a test are shown in Figure 3. The data are presented in ascending order within each test. In this case, a high similarity value implies that the two optotypes are similar to each other and therefore that the pair is hard to discriminate. To test for statistically significant differences in pairwise simi-

TABLE 1 (continued). Confusion Matrices

Patti Pics							
	Response						
	Sq	Ap	Cir	Star	Hou		
Stimulus							
Square	187	30	35	34	34		
Apple	37	206	26	24	27		
Circle	43	34	171	31	41		
Star	32	18	29	227	14		
House	33	22	28	11	226		
PV Numbers							
	Response						
	2	3	5	6	9		
Stimulus							
2	240	23	21	15	21		
3	27	208	27	24	34		
5	18	24	221	33	24		
6	16	23	35	219	27		
9	23	32	30	27	208		
Lighthouse							
	Response						
	House	Umbrella	Apple				
Stimulus							
H	132	9		19			
U	2	146		12			
A	19	19		122			
Allen							
	Response						
	Tr	Ca	Je	Ph	Be	Hor	Hou
Stimulus							
Tree	471	2	0	0	7	0	0
Cake	0	453	0	9	6	6	6
Jeep	1	0	477	1	0	1	0
Phone	0	17	2	450	1	2	8
Bear	0	3	0	0	454	5	18
Horse	0	13	0	0	2	459	6
House	2	2	0	2	16	4	454

larity, the model fit with all similarities free to vary was compared to a restricted model in which the similarities were forced to be equal for all pairs in the test. The fit comparison was assessed with a G^2 likelihood-ratio test.²⁶ A significant P value indicates that some pairwise similarities were significantly different from others within a test. The Landolt C ($P = 0.09$), Lea numbers ($P = 0.08$), Lea Symbols ($P = 0.57$), and Tumbling E ($P = 0.11$) tests all had insignificant P values, and therefore it was not possible to reject the hypothesis that their pair similarities were equal within these tests. The Allen figures, HOTV, Lighthouse, Patti Pics, and Precision Vision numbers tests all generated significant P values ($P < 0.0001$), indicating that the similarities were not equal across optotype pairs (as shown in Fig. 3). Analogous tests of the response-bias parameters, with α set to

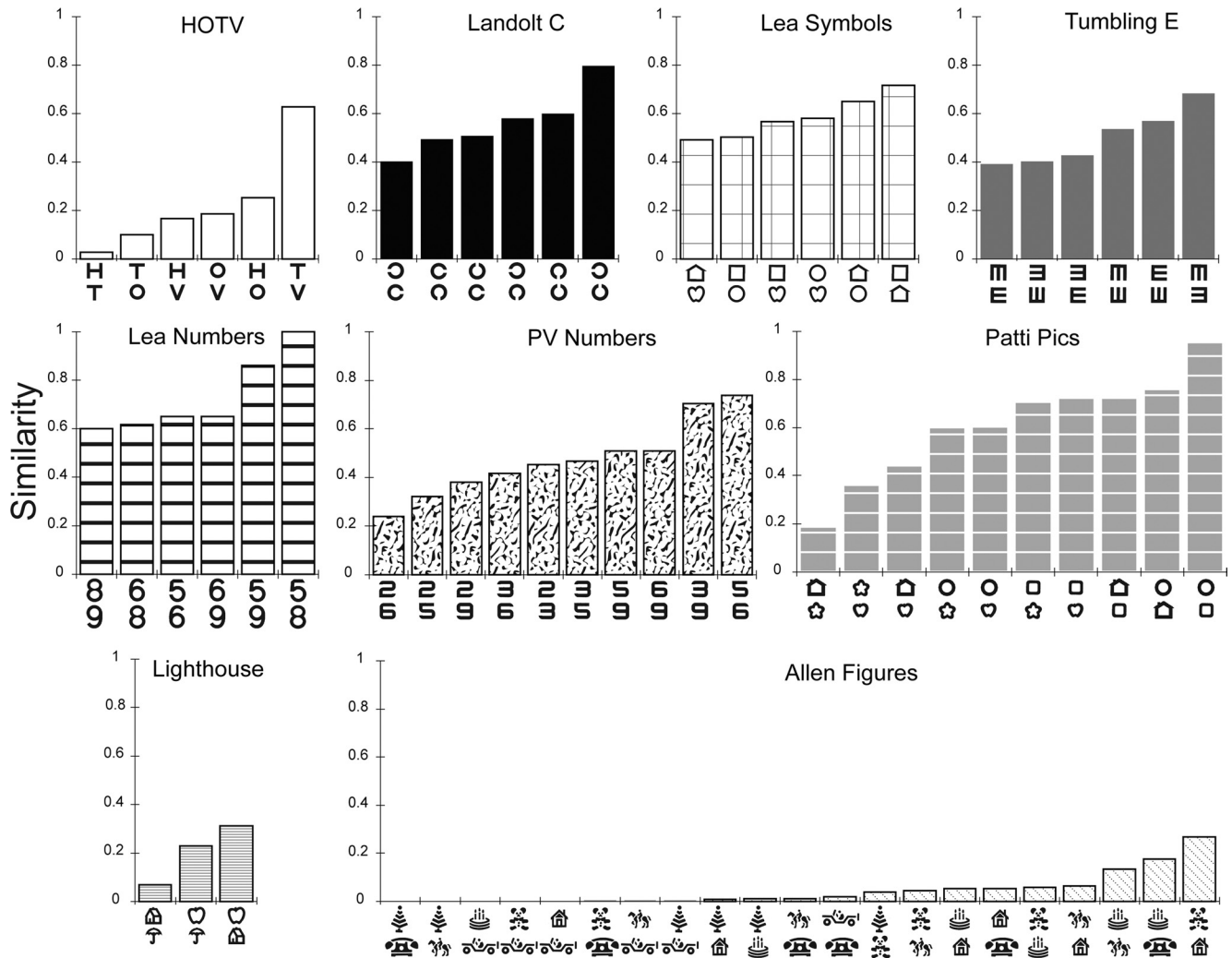


FIGURE 3. Similarity values for each pair of optotypes within each test, derived from Luce's biased-choice model. A value of 1 represents the similarity of an optotype to itself, and therefore a low similarity value indicates that the pair can be discriminated easily. The relevant pair of optotypes is presented below the x-axis.

0.01, indicated that the biases were not significantly different across optotypes within all tests apart from the HOTV test ($P = 0.0002$). The subjects demonstrated a small bias toward responding "T" and away from responding "O" for that test.

DISCUSSION

Assessment of VA

The data presented in Figure 1 indicate that a within-subject comparison of acuity estimates across the tests produces differing values. Taking the Landolt C test as the standard reference,¹ the mean acuities of the Allen figures and HOTV test were significantly better than the Landolt C at this sample size, by at least a chart line (0.1 log unit). Comparing these data with the percent incorrect data in Figure 1B indicates a similar relationship, with the addition of a significant difference for the Lighthouse test, as it was no longer subject to the floor effect found in the acuity data. Although the effect of crowding was not explicitly tested in this study, it is interesting to note that all the tests, apart from the Allen figures, were presented in line format for the acuity measurements shown in Figure 1A, whereas they were all presented in isolated, uncrowded format

for the paired optotype psychophysics presented in Figure 1B. The Allen, HOTV, and Lighthouse optotypes all remained easier to discriminate than the Landolt C when line interaction or crowding effects were eliminated.

These data, collected from adults with typical acuities, are consistent with the previous pediatric literature, in that acuities recorded with a crowded HOTV test have been found to be finer (better) on average than those recorded with the ETDRS test for 5- to 12-year-olds,^{20,24} and finer on average than those recorded with the Lea Symbols for 3- to 3.5-year olds¹⁹ and amblyopic subjects from 4 to 35 years of age.²⁷ The isolated Allen figures have also been found to be insensitive to amblyopic vision loss in comparison with Snellen letters.^{23,28} Thus, although adults were tested in the present study to reduce variability and increase data collection, this consistency with the pediatric literature suggests that the factors underlying differences in the measured adult acuities may also affect the acuities collected from developing visual systems. Of note, the present study did not find the approximately half-line difference between the Lea Symbols and ETDRS chart results noted by Dobson et al.²¹ for astigmatic children, possibly as a result of the meridian-specific blurring characteristics of astigmatic blur.

The data presented in Figure 2 demonstrate that the overall percent correct for each optotype also varies within tests. This result has important practical relevance in situations where an examiner may test only a few optotypes from any one line on a chart. In particular, examiners can reach differing acuity results depending on the optotypes they select. The internal consistency of a test is therefore important in addition to the overall mean performance of the test chart. The data in Figure 2 indicate that most charts have a range of percent correct values of 10% or less across their optotypes. Only the Lighthouse figures and the Patti Pics currently have ranges greater than ten percent. It should be noted that the Allen figures demonstrated a ceiling effect that limited the range, in that some optotypes produced almost 100% correct performance.

Assessment of Similarity

The second, pairwise comparison, phase of this study addressed a different question. When acuity tests are presented in a protocol that requires the subject or patient to perform a discrimination task, such as matching targets on a card, or when larger versions of the optotypes are available on the chart for comparison, the subject is really being asked to discriminate between the possible response options. Correct performance on this task depends on the information available in the differences between the optotypes, rather than the smallest detail available in each optotype.^{3,5,29,30} An example of the difference between two optotypes is presented in Figure 4. The regions shown in gray are common to both optotypes, the regions in white are unique to the circle, and the regions shown in black are unique to the apple. Some of this difference information must be visible to subjects for them to be able to respond correctly. Therefore, the measured acuity reflects the availability of this information to the subject as optotype size decreases and approaches threshold. A difference image containing significant amounts of low-spatial-frequency information implies that the discrimination will be easy to perform. The second phase of this study was therefore designed to systematically assess the differences between optotypes in each test. The uncrowded, isolated optotype presentation was used to assess the impact of optotype design directly, while removing complicating interaction effects resulting from crowding.

The results presented in Figure 3 indicate that, for most of the tests, the individual pairs of optotypes had different similarity values. In particular, within the Allen figures, HOTV,

Lighthouse, Patti Pics, and Precision Vision numbers tests, the differences in similarity values across the pairs of optotypes were statistically significant. (Care should be taken in interpreting the Allen figures data, as the subjects were all so close to a 100% correct performance that the similarity values suffer from a floor effect. The full range of similarities was likely to have been hidden by the limit of 100% correct performance, although the similarity values were still significantly different from each other.)

Implications for Clinical Testing of Children

This study was conducted on adult subjects with no ocular disorders and with optical correction to provide typical acuities. These acuity tests are designed to be used with young children, however. It is possible that the results would differ somewhat for children and/or for patients with clinical conditions. The adult data are still important, however, as they reveal the fundamental limitations of the optotype design, without the additional confounds of astigmatic blur, pathology, or immature cognition and attention, for example. In support, these data are qualitatively consistent with the pediatric literature and demonstrate that differences in acuity estimates resulting from basic differences in optotype design and combination are likely to have a significant impact on children's performance. This set of results now needs to be tested in the relevant pediatric populations, who may not be capable of providing the full set of data.

CONCLUSIONS

As observed in the literature regarding children,^{10,19–25} this study demonstrated that adult subjects with no ocular disorders generate varying acuity estimates when completing a battery of commonly used pediatric acuity tests. An analysis of the similarities of optotypes within these tests also indicated that optotype discrimination performance varied within some tests. The data suggest that the Allen figures, HOTV, Lighthouse, Patti Pics, and Precision Vision numbers tests could all be improved in terms of the uniformity of the pairwise similarity across optotypes, and that the Allen figures, HOTV, and Lighthouse tests could all be improved in terms of their percent correct equivalence to the standard Landolt C test. It is hoped that these data will be useful to clinicians and vision scientists, as well as to the designers and manufacturers of tests.

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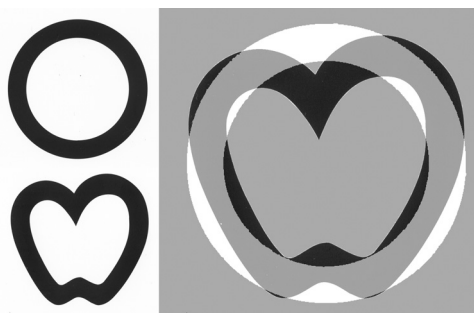


FIGURE 4. A demonstration of the information available in the difference between two Lea symbol optotypes. The two symbols are shown on the left of the figure and the information available in the difference is shown on the right. The area shown in white, in the right panel, represents the information unique to one optotype, whereas the area unique to the other is shown in black. The amplitude spectrum of this difference indicates the information available to discriminate the two symbols. This information is at least partially dependent on the relative alignment of the two optotypes.

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